Quantum Gravity in a Laboratory?

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based on work with Niels Linnemann and Mike Schneider

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0. Novel QG predictions are (very) hard to test

- As customary, I start by noting how hard it is to test predictions of quantum gravity (QG).
    - Insofar as the predictions of GR or QM are recovered, that's not true.
    - It depends on what you mean by 'QG' [W21]. If you include QG-as-EFT, then:
        - in the mean field, 'semiclassical gravity' sector, there are tested novel predictions.
        - the inflaton field account of CMB structure involves spacetime superposition.
- But can we experimentally observe the characteristically 'quantum nature' of *gravity*?
    - For instance, a gravitational version of the photoelectric effect? But for the n=2 to n=1 transition the EPE is ~10eV, but the GPE is ~10^{-38}eV, so this is impractical.
    - For instance, a more promising approach might be to see decoherence between a material system and gravitons.
    - Or, in the study of 'gravitational Schrödinger cats' ('gravcats') – systems small enough to maintain quantum coherence, but heavy enough to gravitate.

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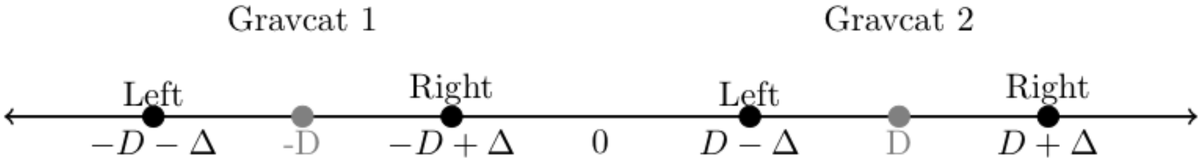
Part One: physics

1. Gravcats: the naive model

- Suppose two gravcats (say, 10^{-14}kg diamonds), *separable* but in superposition:

$$\Psi(0) = (|L\rangle + |R\rangle) \otimes (|L\rangle + |R\rangle) = |L\rangle \otimes |L\rangle + |L\rangle \otimes |R\rangle + |R\rangle \otimes |L\rangle + |R\rangle \otimes |R\rangle$$



  - Each term corresponds to a different gravitational potential, so phase shifts result:

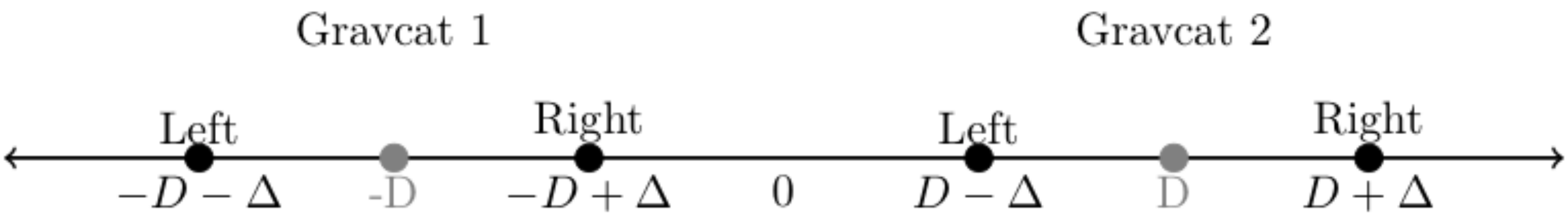
$$\Psi(t) = e^{\frac{-iGm^2t}{2D}}|L\rangle \otimes |L\rangle + e^{\frac{-iGm^2t}{2D+2\Delta}}|L\rangle \otimes |R\rangle + e^{\frac{-iGm^2t}{2D-2\Delta}}|R\rangle \otimes |L\rangle + e^{\frac{-iGm^2t}{2D}}|R\rangle \otimes |R\rangle,$$

an observably *entangled* state.

- Claim: such gravitationally induced entanglement (GIE) would be a '*witness*', or indirect observation, of the *quantum* nature of gravity [B&al17][M&V17][C&R19].
  - But would it? After all, we simply appealed to a $\hat{V} = \dfrac{Gm^2}{|\hat{x}_1 - \hat{x}_2|}$ potential, which (even with hats) doesn't look very interestingly quantum.

2. Gravcats vs semiclassical gravity

- Even at this level of analysis, entanglement is incompatible with semiclassical gravity, as given by the Einstein-Møller-Rosen equation: $G_{\mu\nu} = \frac{8\pi G}{c^4}\langle \hat{T}_{\mu\nu}\rangle_{\Psi_{matter}}$.
  - In SCG (ignoring self-gravity) each gravcat thus sees a potential centered at the *expected position* of the other ($\pm D$): e.g., for the left packet of gravcat 1 $V_{L1} = Gm^2/(2D+\Delta)$.



$$V_{L1} = \frac{Gm^2}{2D+\Delta} \qquad V_{R1} = \frac{Gm^2}{2D-\Delta} \qquad V_{L2} = \frac{Gm^2}{2D-\Delta} \qquad V_{R2} = \frac{Gm^2}{2D+\Delta}$$

$$\Psi(t) = e^{-iV_{L1}t}|L\rangle \otimes e^{-iV_{L2}t}|L\rangle + e^{-iV_{L1}t}|L\rangle \otimes e^{-iV_{R2}t}|R\rangle + e^{-iV_{R1}t}|R\rangle \otimes e^{-iV_{L2}t}|L\rangle + e^{-iV_{R1}t}|R\rangle \otimes e^{-iV_{R2}t}|R\rangle$$

$$= \left(e^{-iV_{L1}t}|L\rangle + e^{-iV_{R1}t}|R\rangle\right) \otimes \left(e^{-iV_{L2}t}|L\rangle + e^{-iV_{R2}t}|R\rangle\right)$$

  - The wavefunction after the interaction factorizes, so SCG does not predict entanglement.

- But is that to witness the ***quantum*** nature of gravity? And is ruling out SCG important?

3. Gravcats: the Newtonian model

- To understand better, let’s start with more fundamental physics: QFT and GR [A&H14].
  - Start with GR with scalar matter, linearize in Minkowski spacetime, and gauge fix:

$$H = \xcancel{H_{KG}} - G\int d\mathbf{r}\int d\mathbf{r}'\frac{\epsilon(\mathbf{r})\epsilon(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} - 4\pi G\xcancel{\int d}\mathbf{r}\bar{\gamma}^{ij}t_{ij} + \xcancel{H_{\gamma\gamma}} + \xcancel{\ldots}$$

  $\epsilon(r)$ is the matter density, t_{ij} stress-energy, and $\bar{\gamma}^{ij}$ metric perturbations.

  - However, in the GIE calculation, H_{KG} and perturbations can be neglected, so the Hamiltonian reduces to $\hat{H} = \dfrac{Gm^2}{|\hat{x}_1 - \hat{x}_2|}$ on quantization – as in the naive model.

- This Newtonian term (i) arises from the gauge constraint, and (ii) is fully determined by the instantaneous matter distribution: from a gauge theoretic POV the ‘true’ degrees of freedom all lie in the metric perturbations – gravitons, since quantized.
  - But gravitons are not involved in the relative phases, so in <u>that</u> sense GIE does not ‘truly’ witness the quantum nature of *<u>gravity</u>* at all! [ALS21]

4. Gravcats: Tripartite models

- But what about the lesson of the past 200 years that gravity is dynamic and causal?
- Simplemindedly, the initial state is tri- not bi-partite, two gravcats <u>plus</u> gravity:

$$|L\rangle \otimes |\gamma_{LL}\rangle \otimes |L\rangle + |L\rangle \otimes |\gamma_{LR}\rangle \otimes |R\rangle + |R\rangle \otimes |\gamma_{RL}\rangle \otimes |L\rangle + |R\rangle \otimes |\gamma_{RR}\rangle \otimes |R\rangle$$

  - E.g., each $|\gamma\rangle$ could be a definite state of metric geometry associated to each gravcat pair: say, $ds^2 = (1 - 2\phi(\mathbf{x}))dt^2 - d\mathbf{x}^2$ (with $\phi(\mathbf{x}) = Gm/r$ outside, $\phi(\mathbf{x}) = Gm/R$).
  - Then [C&R19] different terms correspond to gravcat trajectories with different proper times, so relative phases due to time dilation – equal to those of the Newtonian model.
  - GIE gives witness to a <u>*quantum*</u> superposition of gravity!
- We motivated this approach with causality, but that's not essential: the same result holds in Newton-Cartan gravity. (Also with coherent states of the graviton field [B&al17].)
  - What matters is that gravity be an interaction-mediating subsystem. Then theorems say it must be non-classical if the gravcats entangle [M&V17, 20; GGS22]: witnessing as *dependence* of some observation on non-classicality of gravity.

Part Two: interpretation

5. *Quantum* gravity in a laboratory?

- According to the Newtonian model gravcats do not witness quantum *gravity*, since only the gauge fixed term plays a role …

$$H = \xcancel{H_{KG}} - G\int d\mathbf{r}\int d\mathbf{r}'\frac{\epsilon(\mathbf{r})\epsilon(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} - 4\pi G\xcancel{\int d\mathbf{r}}\bar{\gamma}^{ij}t_{ij} + \xcancel{H_{\gamma\gamma}} + \xcancel{\ldots}$$

- … while according to a Tripartite model they do, since only if gravity is a *quantum* intermediary can it produce GIE …

$$|L\rangle \otimes |\gamma_{LL}\rangle \otimes |L\rangle + |L\rangle \otimes |\gamma_{LR}\rangle \otimes |R\rangle + |R\rangle \otimes |\gamma_{RL}\rangle \otimes |L\rangle + |R\rangle \otimes |\gamma_{RR}\rangle \otimes |R\rangle$$

… so which is the *correct* way to model the experiment?

- To some degree a bad question, since it assumes that fundamental physics always yields a unique approximate model.

- Indeed, both models involve reasonable theoretical stances, so perhaps the issue is just theory-laden. Then the thing to do is clarify the competing theoretical perspectives.
  - (a) reconstruct competing assumptions; (b) do they settle the debate? (No!)

5. *Quantum* gravity in a laboratory?

- Newtonian model: applicability of standard gauge quantization and lore to GR –
    - the so-called ‘true’ degrees of freedom do not play a role.
    - the whole effect is due to a Newtonian potential.
- But what is it to be a ‘true’ degree of freedom? Do they constitute ‘gravity’?
    - the gauged vs free split is partially dependent on the choice of gauge.
    - different potentials are physically different, even if fixed by matter.
    - which is why the Newtonian potential was ‘gravity’ until GR!
- So it’s ontologically tendencious to say that the interaction is not ‘truly’ part of the gravitational field.
- Nonetheless, the question of whether $\hat{V} = \frac{Gm^2}{|\hat{x}_1 - \hat{x}_2|}$ alone is ‘quantum’ (or at least ‘non-classical’) remains: especially as it is gauge, not dynamical.

5. *Quantum* gravity in a laboratory?

- Tripartite model: gravity is an intermediary subsystem (motivated by spacetime causality).
- Some might resist this assumption:
    - by *neutrality* on whether the EFT approach to GR is valid,
    - or by countenancing an *alternative* way to combine the quantum with gravity.
- However, amongst QG theorists the EFT approach to GR is widely accepted as valid:
    - even the weaker assumptions of the no-go theorems then entail (given GIE) a quantum spacetime superposition (more carefully, a 'non-classical' state).
- Nevertheless, someone with such theoretical commitments might still hold that the Newtonian, not tripartite, model is appropriate to a gravcat experiment, so that in the most important sense, GIE does <u>not</u> witness the quantum nature of spacetime:
    - maxim: in case of empirical equivalence, prefer models that idealize more,
    - after all, gravity is only a gauge constraint in the experiment, not dynamical,
    - a stronger witness would be entanglement *with* gravitons [B&al18].

6. Why perform the experiment?

- The experiment is partly motivated to rule out SCG (as a fundamental theory) – yet few involved take that as a serious contender. So why (else) go to the expense and effort?
  - Perhaps because of the high epistemic standards of science, SCG must be refuted…
  - … but not to test predictions distinguishing different theories of QG… at least at first.
  - Because one accepts the EFT approach to GR, or even the tripartite model as appropriate for gravcats, so entanglement witnesses the quantum nature of gravity.
  - But experimental science is about more than just testing, it is about gaining control of new physical regimes – ‘know how’, as well as ‘knowing that’.
    - Pushing beyond quantum neutron interferometry in the Earth’s gravity. [COW75]
  - Of course in part for practical purposes and to develop the technology for future tests, but also to ‘make real’ in the laboratory the ‘merely’ theoretical.

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